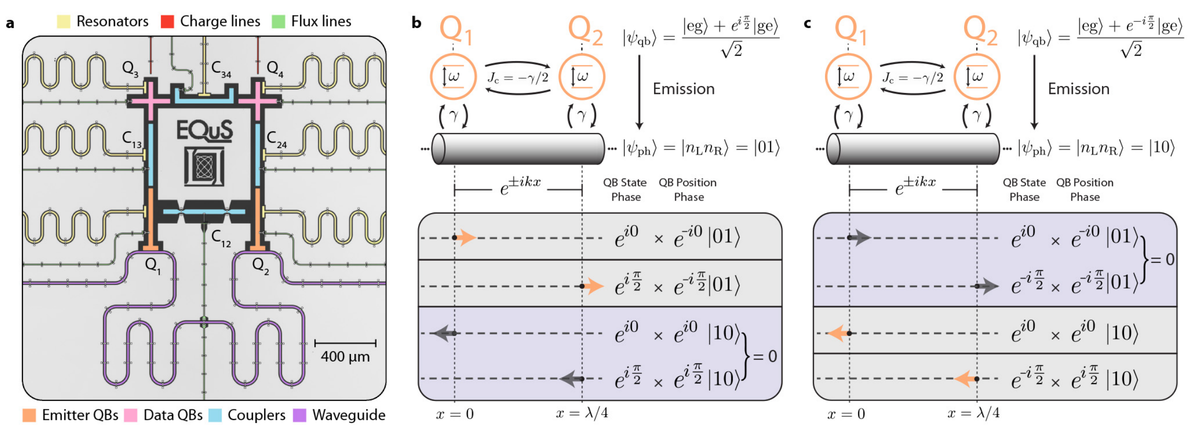
Photonics and Optoelectronics

On-demand Directional Photon Emission Using Waveguide Quantum Electrodynamics

B. Kannan, A. Almanakly, Y. Sung, A. Di Paolo, D. A. Rower, J. Braumuller, A. Melville, B. M. Niedzielski, A. Karamlou, K. Serniak, A. Vepsalainen, M. E. Schwartz, J. L. Yoder, R. Winik, J. I-Jan Wang, T. P. Orlando, S. Gustavsson, J. A. Grover, W. D. Oliver
Sponsorship: AWS Center for Quantum Computing, Department of Defense, US Army Research Office, Department of Energy Office of Science - National Quantum Information Science

Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Quantum information can be transferred between arbitrary nodes by photons that propagate between them or by resonantly coupling nearby nodes. Notably, conventional approaches involving propagating photons have limited fidelity due to photon loss and are often unidirectional, whereas architectures that use direct resonant coupling are bidirectional in principle but can generally accommodate only a few local nodes. Here, we demonstrate high-fidelity, on-demand, bidirectional photon emission using an artificial molecule comprising two superconducting qubits strongly coupled to a waveguide. Quantum interference between the photon emission pathways from the molecule generate single photons that selectively propagate in a chosen direction. This architecture is capable of both photon emission and capture and can be tiled in series to form an extensible network of quantum processors with all-to-all connectivity.



▲Figure 1: a) A false-colored optical micrograph of the device. b) Schematic outlining the quantum interference effect that enables the emission of a rightward-propagating photon in the waveguide. c) Same as b) but for a leftward-propagating photon.

FURTHER READING:

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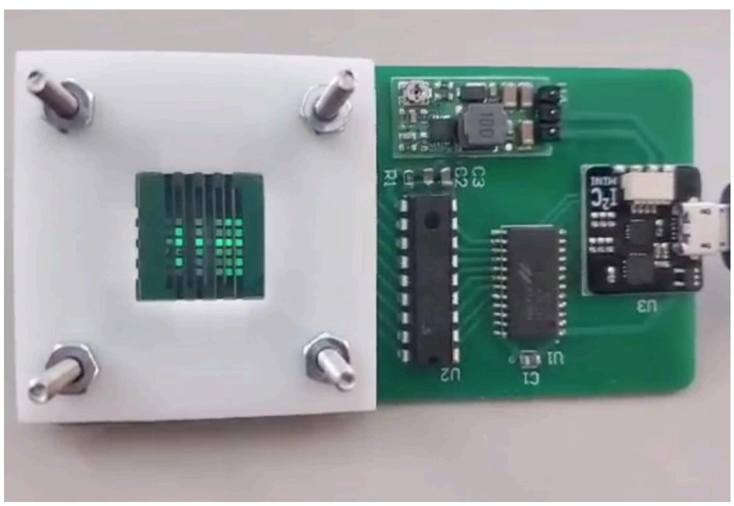
Programmable Organic Light-emitting Diode (OLED) Matrix

S. Cheung*, B. John*, S. Moezzi*, M. Saravanapavanantham, R. Ram, F. Niroui
*Contributed equally
Sponsorship: MIT EECS, 6.S059 class

Organic light-emitting diodes (OLEDs) have reached commercial prominence in recent decades for their improved image quality, durability, and lower power consumption. Future developments in OLED performance can engender the next generation of electronics, including flexible transparent devices. Either a passive-matrix (PMOLED) or active-matrix (AMOLED) control scheme can drive the OLED display. Although PMOLEDs use a simpler, less efficient single pixel control scheme, they are optimal for small displays due to their lack of thin film transistors (TFTs) and resulting low manufacturing cost. Here, we demonstrate a programmable PMOLED matrix with the ability to control individual pixels. Using a device architecture verified from Zou et al., w e fabricated an 8x8 OLED display and designed a printed circuit board (PCB) to control the OLED through custom driver software. The simple and inexpensive manufacturing process highlights the potential for ubiquitous PMOLED displays in everyday consumer lifestyles.



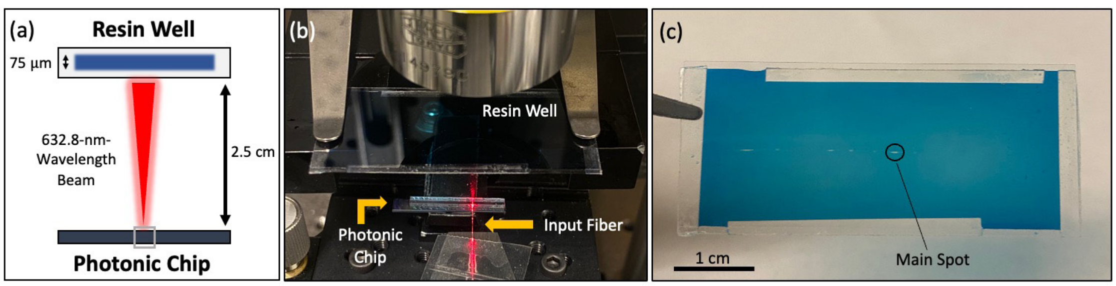
▲ Figure 1: Photograph of the OLED matrix display held by a 3D printed substrate holder, alongside the custom-designed PCB.

Silicon Photonics for Chip-Based 3D Printing

S. Corsetti, M. Notaros, T. Sneh, A. Stafford, Z. Page, J. Notaros
Sponsorship: MIT Rolf G. Locher Endowed Fellowship

3D printing has contributed to diverse scientific advancements in fields ranging from personal healthcare to soft robotics. To maximize build speed while minimizing material strain, modern laser-based 3D printers rely on intricate mechanical systems. The cost and upkeep of these systems, in addition to the UV-wavelength laser printing standard, have historically presented a barrier for the implementation of 3D printing in low-cost and sensitive-material applications, such as live-cell hydrogel printing.

To address these cost and material constraints, in this work, we combine the fields of silicon photonics and polymer chemistry to develop an on-chip integrated photonic system that enables dynamic non-mechanical control of visible light and controllably cure a custom visible-light-curable liquid resin. This research takes the first step towards a system that will allow for non-mechanical, volumetric 3D printing with interference patterns generated by a single chip. The complete development of this technology would allow for a highly-compact, portable, low-cost, high-speed solution for the next generation of 3D printers.



▲ Figure 1: (a) Conceptual diagram (not to scale) of the system with a photonic chip emitting red light into a glass resin well. (b) Photograph of the experimental setup, in which an input fiber couples 632.8-nm-wavelength light onto the photonic chip that projects a beam upwards into a prototype resin well. (c) Photograph of resin regions selectively cured using the chip, with the curing resulting from the main lobe labeled.

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- M. Notaros, T. Dyer, M. Raval, C. Baiocco, J. Notaros, and M. R. Watts, "Integrated Visible-light Liquid-crystal-based Phase Modulators," *Opt. Express*, vol. 30, pp. 13790-13801, 2022.
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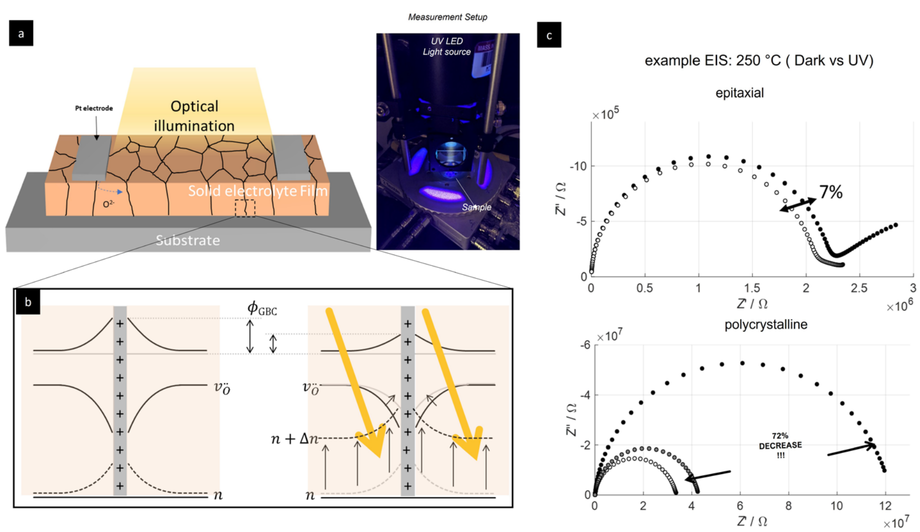
Photo-Enhanced Ionic Conductivity across Grain Boundaries in Polycrystalline Ceramics

T. Defferriere, D. Klotz, J. C. Gonzalez-Rosillo, J. L. M. Rupp, H. L. Tuller
Sponsorship: DoE, Japan Society for The Promotion Of Science, Kakenhi Grant-In-Aid, Swiss National Science Foundation, Equinor

Oxide based ionic conductors are critical for energy conversion and storage devices such as fuel cells or batteries, or for nano-electronic memory and gas sensing devices. However, cost-effective fabrication methods for both bulk and thin films samples often result in polycrystalline microstructures whose grain boundaries block ion migration. This has been explained by space-charge potential barriers, featuring depletion zones and band bending, forming between adjacent grains, which typically limits the overall material conductivity, particularly as one approaches ambient temperatures. Above bandgap light is known to reduce band bending at interfaces in photovoltaic and photoelectrochemical systems by providing photogenerated charge carriers that screen potential barriers. We demonstrate here that the same principle (Figure a and b) applies to a solid-state oxygen ion conductor and that we can decrease its grain boundary resistance by optical illumination. We further demonstrated that this effect is not caused by heat or electronic conductivity. Our conclusions are based on electrochemical impedance spectroscopy (Figure c) and intensity-modulated photocurrent spectroscopy (IMPS) measurements, performed on polycrystalline and epitaxial samples, and backed by theoretical considerations of grain boundary potential heights and distributions. This discovered effect has the potential to lead to improved electrochemical storage and conversion efficiencies and reduced temperature operation as well as offering contactless diagnosis of ionic conduction in polycrystalline solids.



▲Figure 1: (a) Schematic of polycrystalline oxide-based oxygen solid electrolyte thin film and the optical setup used to characterize sample conductivity under illumination, (b) Simplified diagram of grain boundary space charge potential modulation by above band gap optical illumination and the induced change in band bending. (c) Electrochemical impedance spectroscopy (EIS) results obtained at 250°C in the dark (black circle) and under UV illumination (brighter circles) for epitaxial and polycrystalline sample's demonstrating large resistance decrease only in the polycrystalline sample.

FURTHER READING

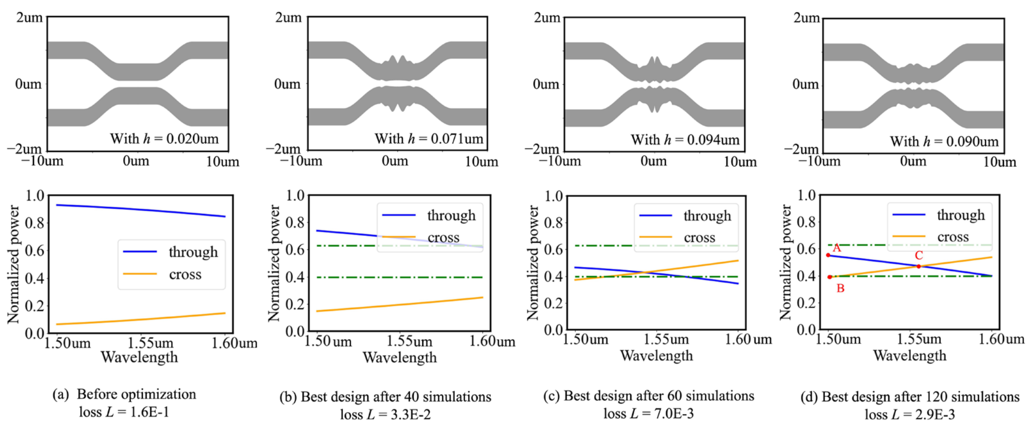
- T. Defferriere, D. Klotz, J. C. Gonzalez-Rosillo, J. L. M. Rupp & H. L. Tuller "Photo-enhanced Ionic Conductivity Across Grain Boundaries in Polycrystalline Ceramics." *Nat. Mater*. 21, 438-444 (2022).

Automatic Design of a Broadband Directional Coupler via Bayesian Optimization

Z. Gao, Z. Zhang, D. S. Boning

Integrated silicon photonics has emerged as an attractive technology that brings breakthroughs in data communications, super-computing, etc. Directional couplers (DCs) are an important device in integrated silicon photonics, due to their capability to realize complicated functionalities. During the past few decades, a DC operating in broadband is of high interest to researchers, and various design methods have been proposed. However, all of these methods rely on the knowledge of design experts and manual adjustment of design parameters (e.g., the height of the rib or the width of the waveguide).

In this work, we propose a fully automatic design method to synthesize a broadband DC via Bayesian optimization. Bayesian optimization is a gradient-free black-box global optimization technique, made up of two steps in combination: (i) building a surrogate model and (ii) optimizing a user-defined acquisition function. These two steps will be repeatedly performed until the maximum number of iterations is reached. As demonstrated in Figure 1, our simulation results show that within 120 simulations, an initial trivial DC design can be evolved into an attractive broadband one, with an excess loss around 0.27 dB and a maximum imbalance around 16%. The proposed Bayesian optimization method could largely reduce the human effort in designing a broadband DC and shorten the design time.



▲ Figure 1: Minimizing loss L defined on a directional coupler via Bayesian optimization. In (d), points A, B, and C have coordinates (1.50, 0.55), (1.50, 0.39), and (1.56, 0.47), respectively.

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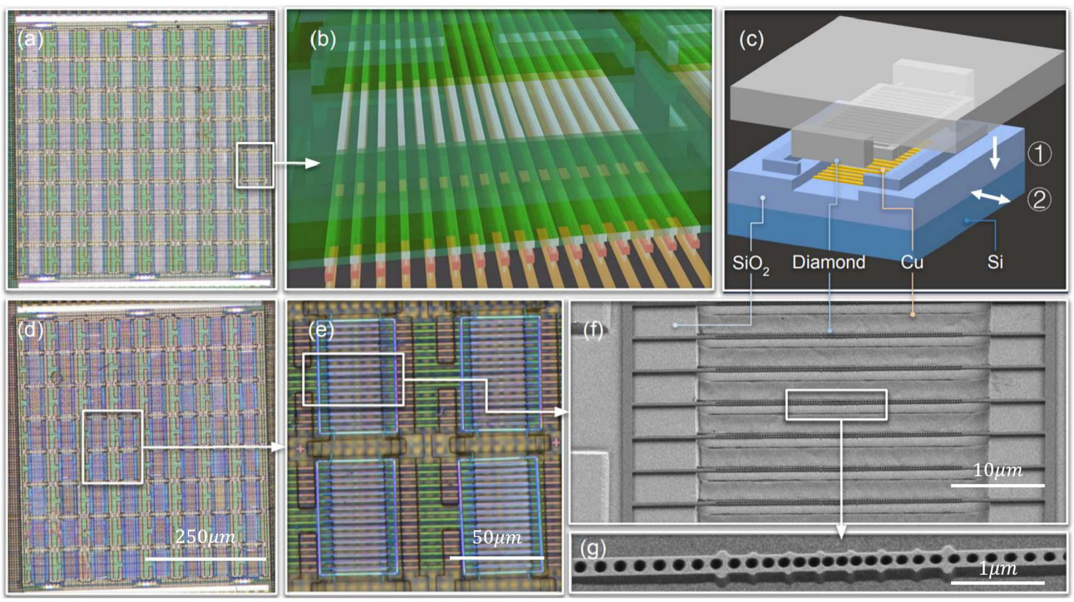
- Z. Gao, Z. Zheng, and D. S. Boning, "Automatic Design of a Broadband Directional Coupler via Bayesian Optimization," *2022 Conference on Lasers and Electro-Optics (CLEO)*, pp. 1-2, 2022.

Scalable Quantum Information Processing Architecture Using a Programmable Array of Spin-photon Interfaces

L. Li, L. D. Santis, I. Harris, K. C. Chen, Y. Song, I. Christen, M. Trusheim, C. E. Herranz, R. Han, D. R. Englund
Sponsorship: MITRE, Center for Integrated Quantum Materials, NSF

A central challenge in quantum information processing is to generate a large-scale entanglement of quantum systems. A leading hardware platform consists of qubits in the form of spin states of color centers in diamond. However, it is estimated that for general-purpose quantum information processors, millions of qubits will be required, motivating the need for hardware architectures that are highly scalable using modern semiconductor integration systems.

Here, we demonstrate a scalable quantum information processing architecture in a proof of concept consisting of a 2D array of tin-vacancy centers, addressable and tunable across thousands of diamond cavities hybrid integrated on a control chip based on the foundry process. We demonstrate core capabilities including tuning of the color center emission wavelength, spin initialization, and single-shot spin readout. The above works together are a proof of concept for a freely scalable architecture capable of hosting thousands toward millions of qubits.



▲Figure 1: (a) The complementary metal-oxide-semiconductor (CMOS) chip after surface post-processing. (b) CMOS chip region marked by the white box in (a) with chiplet locking structure and metal routing. (c) The scalable hybrid integration illustration. (d) The 1024 diamond cavities hybrid integrated on CMOS control chip. (e) The zoom-in optical microscope image. (f) The diamond chiplet scanning electron microscopy (SEM) image. (g) The SEM image of the perturbative cavity design optimized for free space collection.

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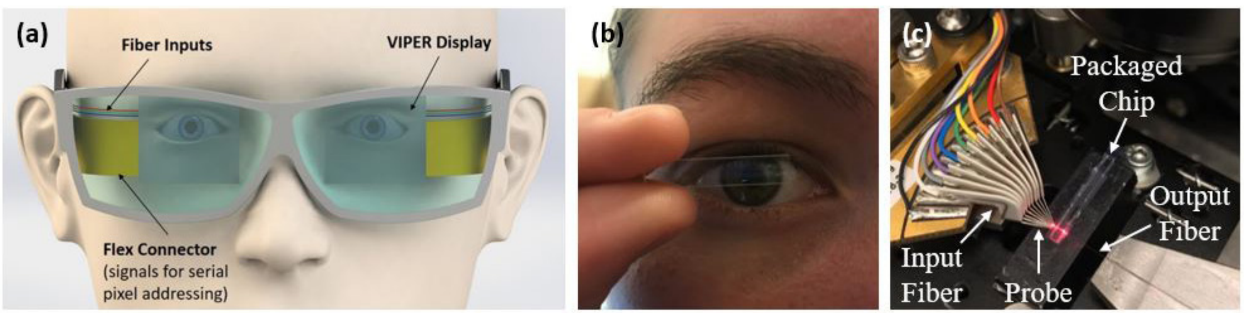
- L. Li, L. D. Santis, I. Harris, K. C. Chen, Y. Song, I. Christen, M. Trusheim, C. E. Herranz, R. Han, and D. Englund. "Scalable Quantum Information Processing Architecture Using a Programmable Array of Spin-photon Interfaces," *CLEO: QELS_Fundamental Science*. Optical Society of America, 2022.

Integrated-Photonics-Based Visible-Light Holographic Augmented-Reality Display

M. Notaros, T. Dyer, M. Raval, C. Baiocco, E. P. Ippen, M. R. Watts, J. Notaros
Sponsorship: DARPA Visible Integrated Photonics Enhanced Reality (VIPER) program (Grant No. FA8650-17-1-7713), NSF Graduate Research Fellowship (Grant No. 1122374)

Augmented-reality head-mounted displays (HMDs) that display information in the user's field of view have many wide-reaching applications in defense, medicine, gaming, etc. However, current commercial HMDs are bulky, heavy, and indiscreet. Moreover, current displays are incapable of producing holographic images with full depth cues; this lack of depth information results in eyestrain and headaches that limit long-term and wide-spread use of these displays (also known as the vergence-accommodation conflict).

In this work, recent advances in the development of a novel integrated-photonics-based holographic display are reviewed. The display consists of a single transparent chip that sits directly in front of the user's eye and projects 3D holograms that only the user can see using amplitude- and phase-encoded liquid-crystal-based integrated optical phased arrays. The display presents a highly discreet and fully holographic solution for the next generation of augmented-reality displays.



▲ Figure 1: (a) Diagram of the chip-based direct-view near-eye head-mounted display. (b) Photograph of a transparent photonic chip held in front of an eye. (c) Photograph of a photonic chip packaged with liquid crystal on an experimental setup.

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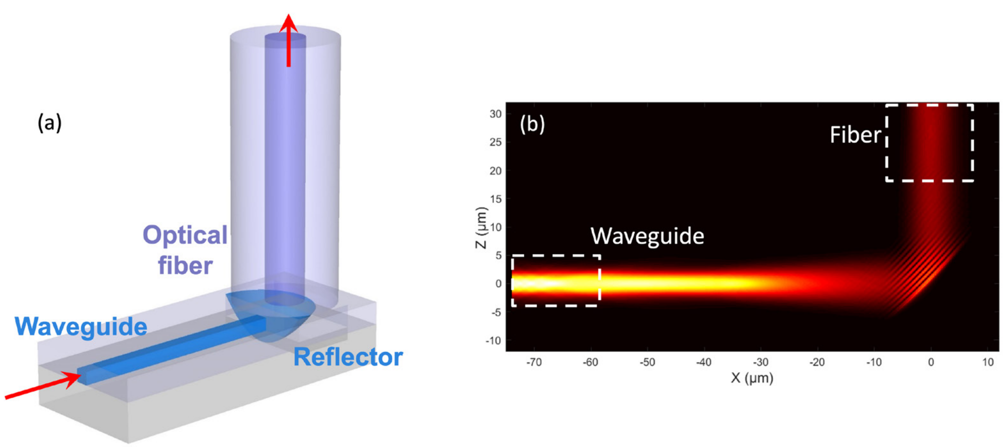
- J. Notaros, M. Raval, M. Notaros, and M. R. Watts, "Integrated-Phased-Array-Based Visible-Light Near-Eye Holographic Projector," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)*, paper STu3O.4, 2019.

3D Printed Micro-reflectors for Broadband, Low-loss and High-density Fiber-to-chip Coupling

L. Ranno, S. Yu, Q. Du, S. Serna, C. McDonough, N. Fahrenkopf, T. Gu, J. Hu
Sponsorship: Advanced Research Projects Agency – Energy (Department of Energy) under the ENLITENED Program (Award Number: DE-AR0000847)

Packaging constitutes a notable fraction of the cost of photonic integrated circuits, mainly due to the challenges related to fiber-to-chip optical coupling, such as the large modal mismatch between fiber and waveguide modes and the resulting tight alignment tolerances. Conventional packaging methods utilizing edge or grating coupling suffer have major limitations such as high insertion losses, low bandwidth density, limited alignment tolerances, or strong wavelength and polarization dependance. We propose a novel coupling scheme that capitalizes on the high resolution and design freedom offered by two-photon polymerization to address the challenges described above. The coupling scheme makes use of free-form reflective micro-optics that are directly printed onto the exposed facet of a waveguide and allow both redirecting the incoming light and expanding the waveguide mode size, improving the coupling efficiency with an optical fiber. We employ Fermat's principle to vastly simplify the free-form shape optimization process from a brute force local optimization of each point, requiring a large number of simulations, down to two single finite difference time domain (FDTD) simulations. The fabrication of the micro-reflectors can be easily included as a backend process in standard photonics foundry runs without any custom requirements. Simulations and experimental results show that the reflectors can reach the record-low insertion loss for surface-normal coupling of 0.5 dB and broadband operation with 1 dB bandwidth exceeding 300 nm, while also exhibiting alignment tolerances over 2 µm, commensurate with the mode profile of the optical fiber being used and compatible with passive alignment schemes. The micro-reflectors also boast high bandwidth densities and solder reflow compatibility, making them a promising coupling solution for applications ranging from wavelength division multiplexing telecommunications to non-linear optics or broadband sensing.



▲ Figure 1: (a) Schematic showing the structure described in the main text, where a TPP reflector is printed directly on a waveguide facet. (b) FDTD simulation of light coupling from a silicon nitride waveguide into an SMF-28 fiber mediated by an optimized micro-reflector.

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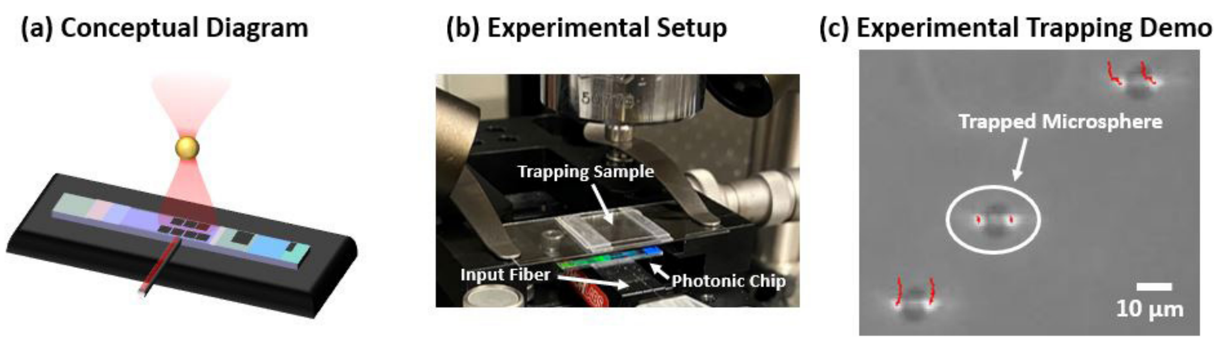
- S. Yu, J. Lu, V. Ginis, S. Kheifets, S. W. D. Lim, M. Qiu, T. Gu, J. Hu, and F. Capasso. "On-chip Optical Tweezers Based on Freeform Optics," *Optica*. vol. 8, pp. 409-414, 2021.

CMOS-Compatible Focusing Optical Phased Arrays for Steerable Chip-Based Optical Trapping

T. Sneh, S. Corsetti, M. Notaros, J. Notaros
Sponsorship: MIT Frederick R. (1953) and Barbara Cronin Fellowship

Silicon photonics has in recent years seen success in translating complex and expensive bulk optical systems to the chip scale for applications such as LiDAR and holographic displays, with facile manufacturing enabled by existing complementary-metal-oxide-semiconductor technology. Optical traps, which have attracted significant interest for their utility in force measurements, cell measurement, and biophysics research, typically require large optical setups. Existing efforts to bring this tool to the chip scale have been limited to trapping within 100 microns, too short for practical integration with existing research.

In this work, we use integrated optical phased arrays, which enable dynamic spatial control of light, to generate focused light 5 mm above the chip surface and demonstrate trapping of microspheres. This system represents an easy-to-use optical trapping apparatus, with the potential to broaden the availability of optical-trapping technology and act as a force multiplier for biophysics and related research fields.



▲Figure 1: (a) Conceptual diagram (not to scale) of the chip-based optical-trapping system showing a photonic chip emitting a focused beam and trapping a microsphere. (b) Photograph of the experimental setup showing the input optical fiber, photonic chip, and microsphere sample stage. (c) Microscope image of the microspheres in the sample stage with superimposed tracks showing their motion over time (red lines); the motion of the microsphere located at the focal spot of the OPA (circled in white) is significantly reduced compared to its neighbors, indicating successful trapping.

FURTHER READING

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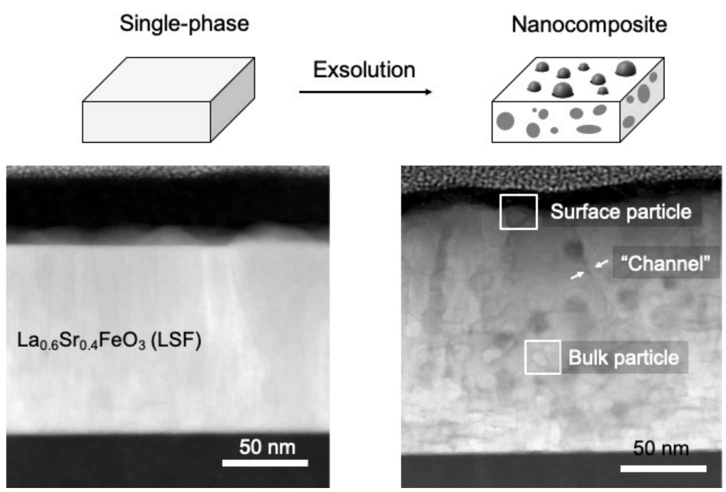
Exsolution Synthesis of Nanocomposite Perovskites with Tunable Electrical and Magnetic Properties

J. Wang, K. Syed, S. Ning, I. Waluyo, A. Hunt, E. J. Crumlin, A. K. Opitz, C. A. Ross, W. J. Bowman, B. Yildiz
Sponsorship: Exelon Corporation, MIT Energy Initiative Seed Fund Program

Nanostructured functional oxides play an important role in clean energy technologies (such as solid oxide fuel cells) and novel memory devices. Here, we present a novel method in fabricating self-assembled nanostructures in a process termed "exsolution." Exsolution is a partial decomposition process in which oxides precipitate nano-scale secondary phases under extreme reducing conditions. Using thin-film perovskites as a model system, we successfully fabricated nanocomposite oxides with exsolution. Moreover, the exsolved nanocomposite is redox-active even at moderate temperatures. Such redox capabilities can enable dynamic control of the nanocomposite functionality by tailoring the oxygen non-stoichiometry. We demonstrate this concept with a continuous modulation of magnetization between 0 and 110 emu/cm3. These findings point out that exsolution may serve as a platform for scalable fabrication of complex metal oxide nanocomposites for electrochemical and electronic applications.



▲Figure 1: Schematics of fabricating self-assembled nanocomposite functional oxides with exsolution.

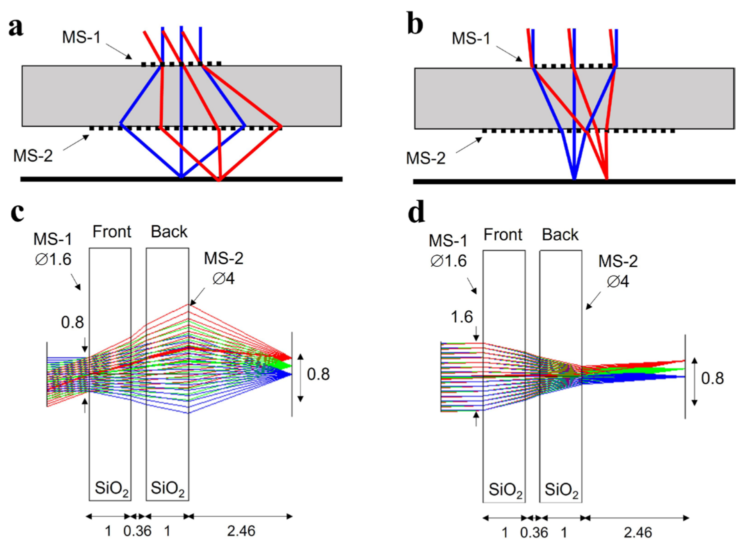
FURTHER READING

• *Adv. Funct. Mater.* 2022, 32, 2108005

Non-mechanical Reconfigurable Zoom Metalenses

F. Yang†, H. Lin†, M. Y. Shalaginov†, K. Stoll, S. An, C. Rivero-Baleine, M. Kang, A. Agarwal, K. Richardson, H. Zhang, J. Hu, T. Gu
†These authors contributed equally to the work
Sponsorships: DARPA Defense Sciences Office Program: EXTREME Optics and Imaging (EXTREME) under agreement no. HR00111720029, MIT Skoltech Seed Fund Program.

Zoom lenses with variable focal lengths and magnification ratios are essential for many optical imaging applications. Conventional zoom lenses are composed of multiple refractive optics; optical zoom is attained via translational motion of one or more lens elements, which adds to module size, complexity, and cost. Here, we present a zoom lens design based on multi-functional optical metasurfaces which achieves large step zoom ratios, minimal distortion and diffraction-limited optical quality without requiring mechanical moving parts. Two embodiments of the concept were experimentally demonstrated based on polarization-multiplexing in the visible and phase change materials in the mid-infrared, both yielding 10x parfocal zoom in accordance with our design.



▲Figure 1: (a)-(b) Schematic illustration of the doublet zoom metalens configuration in the (a) wide-angle mode and (b) telephoto mode. MS-1 and MS-2 label the front and back metasurfaces, respectively. Note that the optical aperture sizes differ in the two imaging modes. (c)-(d) Ray trace simulation of the optimized polarization-multiplexed zoom metalens in the (c) wide-angle mode and (d) telephoto mode. All the units are in mm.

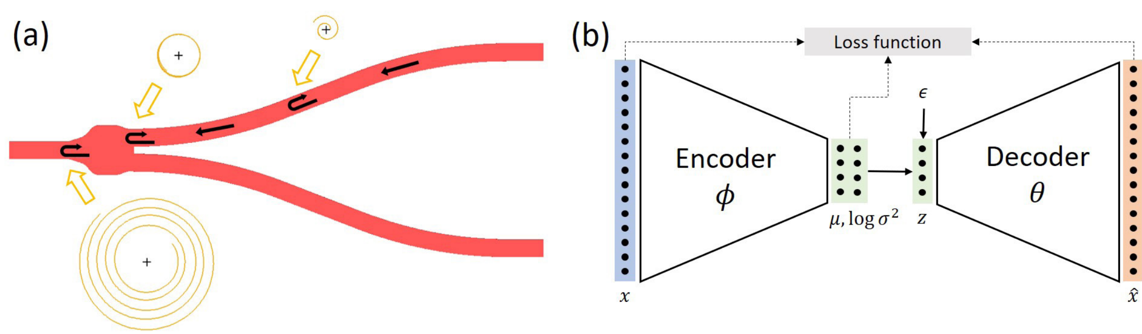
Generative Modeling of Random Process Variation in Silicon Photonics

Z. Zhang, S. I. El-Henawy, D. S. Boning

Silicon photonics, where photons instead of electrons are manipulated, shows promise for higher data rates, lower energy communication and information processing, biomedical sensing, and novel optically based functionality applications such as wavefront engineering and beam steering of light. In silicon photonics, both electrical and optical components can be integrated on the same chip, using a shared silicon integrated circuit (IC) technology base. However, silicon photonics does not yet have mature process, device, and circuit variation models for the existing IC and photonic process steps; this lack presents a key challenge for design in this emerging industry.

Our goal is to develop key elements of a robust design for manufacturability (DFM) methodology for silicon photonics. In particular, generative compact models based on statistics are needed for random process variation analysis to achieve high-yield manufacturing.

In this work, we present two approaches for generative modeling: decomposed S-parameter representation and variational autoencoders (VAE), which ameliorate the issue of non-physical generation due to non-linear behavior of the response. We apply our proposed approaches on Y-splitters with imposed line edge roughness (LER) variations and show their improvement compared to the naïve linear principal component analysis approach. While the decomposed S-parameter representation provides simple generative models for each specific group of LER parameters, the VAE is capable of building a sophisticated model that captures changes from LER parameters and correlation among S-parameters. The method can be extended to other photonic components and circuits with other process variations, providing fast and accurate compact models to help designers predict and optimize photonic component performance, and facilitates the design of high-yield silicon photonic circuits in the future.



▲ Figure 1: (a) Physics behind the decomposed representation, (b) the architecture of the variational autoencoder.

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